Optimal Routing and Data Transmission for Multi-Hop D2D Communications Under Stochastic Interference Constraints

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***Abstract*—In this paper, we aim to determine the multi-hop route between a Device-to-Device (D2D) source-destination pair that maximizes the end-to-end throughput, under stochastic interference constraints imposed by the cellular network and a target SINR constraint at the destination. We determine the maximum allowed D2D transmit powers from the interference constraints and propose a throughput-optimal routing algorithm under a target SINR constraint at the D2D receivers. Also, using elementary queuing theoretic analysis, we derive closed form expressions for throughput and delay under a sequential link activation scheme. Our simulation results show that consideration of channel statistics to determine the optimal route gives higher end-to-end data rates compared to routing based on the path loss only, and highlights the advantages of using a multi-hop route over direct link communication.**

***Index Terms*—Device-to-device communication, routing, interference management.**

I. INTRODUCTION

In traditional cellular networks, all the communication between devices is through the Base Station (BS), even when they are within the communicating radius of each other. This has provided an acceptable quality of service for conventional low data rate mobile services such as voice calling, text messaging, or email. However, with the increase in use of high data rate services, often requested by devices in close proximity, one can achieve significantly better performance by enabling direct links between devices, in addition to reducing the inter-cell interference and improving the spectral efficiency via better frequency reuse. Device-to-Device (D2D) communication, defined as the direct communication between devices without traversing the core cellular network, has recently received much attention in this regard.

One of the open challenges in D2D communications is the routing of data over multiple D2D relay nodes to arrive at the destination and obtain maximum throughput while ensuring that the interference to the core network is kept to a minimum. Although it is not explicitly supported in the standard, multi-hop D2D can be implemented "over the top" in LTE Release 13, by using a User Equipment (UE)-to-Network relay which switches between being a relay and a remote UE. This makes it relevant to consider multi-hop routing between D2D nodes, as it can potentially offer higher data rates when compared to the single-hop direct communication.

Recent research in D2D communication includes the aspects of scheduling [1], resource allocation [2], [3], analysis of interference and coverage [4] and channel modeling [5]. In [6], the authors proposed a scheme for *uplink* D2D, where D2D users listen on a control channel and adjust their operating parameters such that the interference from D2D communication to the cellular link is below a maximum allowed level. In [7], the authors proposed an algorithm in which D2D nodes are associated with interference-limited regions and resources are allocated such that there is no cellular user employing the same resource in these regions.

In practice, when two devices communicate in the D2D mode, the direct path may not be optimal or may become infeasible while satisfying the interference constraint imposed by the cellular network. A higher throughput could be achieved by routing the data through multiple short-range, high-rate links. Towards that, [8] and [9] analyzed the energy efficiency and achievable capacity, respectively, for two-hop D2D communication. In [10], the authors considered multi-hop routing problem and proposed an algorithm to minimize the hop-count between source and destination, under a target rate constraint on the D2D links.

A routing algorithm has been proposed in [11] for downlink-inband D2D considering the path loss between nodes to control the interference to the cellular network while achieving a target SINR at the D2D receivers. However, the routing procedure does not consider the effect of fading in the channels between D2D nodes and between the D2D nodes and the cellular network. This could lead to a sub-optimal route in terms of the achievable throughput, due to the link outages caused by channel fading. Moreover, the interference caused to the cellular network could be higher than that calculated using the path loss component only.

In this paper, we consider the problem of multi-hop routing between a given D2D source and destination, under a stochastic interference constraint imposed by the cellular network.

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Our goal is to determine the route that maximizes the end-to-end throughput, after accounting for link outages due to fading between the D2D nodes. We solve this problem, under a fixed rate communication scheme, in which all the D2D links aim to achieve the same target rate. A fixed rate of communication between D2D nodes is desirable for implementation, as it allows all links to operate using the same modulation and coding scheme. We compute the probabilities with which the D2D links achieve a given target data rate, and apply a routing algorithm on the appropriate cost matrix. Further, under a sequential link activation scheme, we analyze the achievable throughput and the delay incurred by the determined optimal route using elementary queueing theoretic results. The analysis allows us to find the SINR threshold (equivalently, the per-link rate) and corresponding route that maximizes the end-to-end throughput. Finally, using Monte Carlo simulations, we validate the accuracy of our analysis and illustrate the significant improvement in throughput that is achievable by allowing multi-hop D2D communication between nodes.

II. System Model

We consider a network with N BSs and M D2D users deployed in an area of interest [11], as illustrated in Fig. 1. We assume that a D2D source d_S wishes to send data to a D2D destination d_D in the *uplink-inband D2D* mode, where the D2D communication happens in the uplink frequency bands. Uplink-inband D2D is more popular than downlink-inband D2D, as it is known to offer better throughput [12]. In addition to the distance-dependent path loss component, we assume a Rayleigh fading channel between a D2D transmitter d_t and D2D receiver d_r, and between d_t and BS b_s, whose channel fading coefficients are denoted by h_{tr} and h_{tb_s}, and whose average power gains are denoted by σ^2 and σ_{bd}^2, respectively.

To perform optimal routing, we require only the knowledge of the locations of the BSs and D2D users, and not that of the cellular users, while satisfying interference constraints imposed by the cellular network. In this scenario, the D2D users need to manage, and contend with, two kinds of interferences:

(a) Interference from cellular users at the D2D receivers
(b) Interference from D2D transmitters at the cellular BSs.

Further, due to the Rayleigh fading nature of the channel, the observed interference at the BS will exceed any given tolerance limit with nonzero probability, and this should be accounted for in the routing phase. Therefore, we impose probabilistic constraints on the interference caused by the D2D users at the BS, while the D2D users themselves aim to achieve a certain target SINR at their respective receivers. Thus, corresponding to the aforementioned sources of interference, we require that the D2D users satisfy the following constraints:

(a) *Target SINR constraint:* Each D2D receiver requires that its SINR should exceed a threshold γ_{th} for successful data reception. This is because we consider a fixed-rate communication scheme with target rate $\log_2(1+\gamma_{\text{th}})$, and when the SINR $\geq \gamma_{\text{th}}$, each D2D link can achieve the desired target rate. Here, γ_{th} is a design parameter to be chosen later.

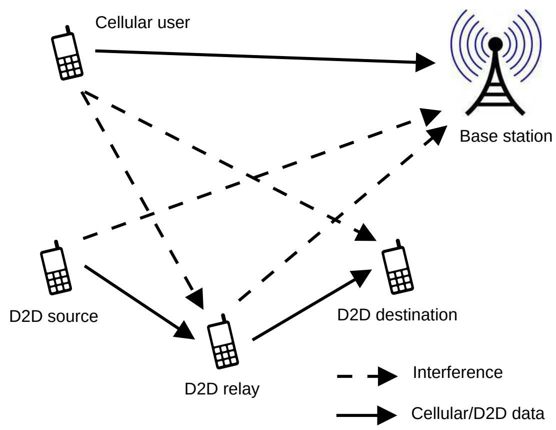

Fig. 1. System model with $N = 1$ BSs and $M = 3$ D2D users

(b) *Interference outage constraint:* The interference caused by a D2D transmitter at all BSs should be below a threshold γ_{bs} dB with probability at least $1-p_b$, similar to [13]. Here, $0 \leq p_b \leq 1$ is called the interference outage probability. Both γ_{bs} and p_b are specified by the cellular network.

Intuitively, there is a tradeoff between γ_{th} and the end-to-end throughput achieved. If γ_{th} is too low, the direct path between the D2D source and destination is feasible with high probability, but the link achieves low throughput. If γ_{th} is very high, each D2D link achieves higher rate, but the direct path may become infeasible with high probability, so that a multi-hop route must be found. However, too many hops in the route can also negatively impact the end-to-end throughput, since the available time for communication must be shared between the hops. Thus, there is an optimal value of γ_{th} that maximizes the end-to-end throughput. Our goal in this paper is to find the throughput-optimal route for communication between the given D2D source and destination, and the corresponding optimal SINR threshold. The optimal route so obtained is used for sequential link activation based data transmission, which requires a 1-bit acknowledgment signal from the destination to the source.

In the next section, we first present a recipe to determine the maximum allowed transmit powers at the D2D nodes. We use this to determine the link outage probabilities between the D2D nodes, which will lead us to an algorithm to find the throughput-optimal path between the given D2D source and destination pair.

III. Proposed Routing Algorithm

The first step in determining the optimal route between the D2D source and destination is to find the maximum power at which each D2D node is allowed to transmit, given the interference constraint imposed by the cellular network. This determines the outage probability of the links when the D2D nodes attempt to communicate with each other at the target rate of $\log_2(1+\gamma_{\text{th}})$, which sets the average rate achieved between pairs of D2D nodes. Using this, we construct a rate matrix between all possible pairs of D2D nodes, which then allows us to use Dijkstra's algorithm to find the throughput optimal route.

A. Determination of maximum allowed transmit power and link outage probabilities

The following recipe determines the maximum allowed transmit power at the t^{th} D2D node, denoted by $P_t^{\max}$, under the interference outage constraint. Next, it uses $P_t^{\max}$ to determine the outage probabilities between all pairs of D2D nodes when they attempt to communicate at the rate determined by the target SINR γ_{th}.

Step 1 The maximum allowed power by the t^{th} D2D transmitter such that the interference outage probability constraint is satisfied at the b_s^{th} BS is calculated using the path loss model and the fading channel between D2D nodes and the BS as follows

$$\begin{aligned} P_t^{\max} = \arg\max_{P_t} \{ & \Pr\{P_t - 10\eta \log D_{tb_s} \\ & + 20\log(|h_{tb_s}|) < \gamma_{\text{bs}}\} \geq (1 - p_b)\} \end{aligned} \tag{1}$$

In the above, η denotes the path loss exponent and D_{tb_s} denotes the distance between the t^{th} D2D node and base station b_s. We require the above constraint to be satisfied at all BSs $s \in \{1, 2, \ldots, N\}$. Hence, the maximum transmit power of a D2D transmitter d_t is limited by the interference it causes to its nearest BS, denoted by b_n. Assuming a Rayleigh fading channel, we obtain the maximum allowed power, $P_t^{\max}$, for every d_t, as follows

$$P_t^{\max} = 10 \log \left(- \frac{10^{\frac{\gamma_{\text{bs}}}{10}} D_{tb_n}^{\eta}}{2\sigma_{\text{bd}}^2 \ln p_b} \right). \tag{2}$$

Step 2 At every D2D receiver d_r, the aggregate interference and noise power, P_r^{int} is measured using an energy or power meter.

Step 3 The transmit power required at a D2D node d_t to meet the target SINR constraint at the D2D receiver d_r is given by

$$\begin{aligned} P_{tr}^{\min} = \arg\min_{P_{tr}} \{ & P_{tr} - 10\eta \log D_{tr} \\ & + 20\log(|h_{tr}|) - P_r^{\text{int}} \geq 10 \log \gamma_{\text{th}}\}. \end{aligned} \tag{3}$$

Step 4 The D2D link $d_t \longrightarrow d_r$ is said to be in outage, or deemed to be infeasible, if $P_{tr}^{\min} > P_t^{\max}$. Therefore, again assuming a Rayleigh fading channel, the outage probability of the link is given by

$$p_{tr}^{\text{out}} = 1 - \exp\left(- \frac{10^{\frac{P_r^{int} + 10\eta \log D_{tr} + 10 \log \gamma_{th} - P_t^{\max}}{10}}}{2\sigma^2} \right). \tag{4}$$

The time complexity of the algorithm presented above is $\mathcal{O}(M^2)$, since we need to compute the maximum allowable transmit power for each of the D2D nodes and the outage probability for all pairs of D2D nodes. Having obtained the outage probabilities with which each of the D2D links can support the target rate, we proceed to find the optimal multi-hop path between the source and destination D2D nodes.

B. Finding the throughput-optimal route

We use the outage probabilities determined above to find the throughput-optimal route between a source d_S and destination d_D for a given target SINR threshold γ_{th}. The steps given below are used to determine the route that maximizes the end-to-end throughput.

Step 1 As determined above, the interference and data outage constraint together set the reliability of any given D2D link. That is, the link $d_t \longrightarrow d_r$ supports the target rate $\log_2(1 + \gamma_{\text{th}})$ with probability $1 - p_{tr}^{\text{out}}$. Therefore, the effective rate of the link is

$$R_{tr} = (1 - p_{tr}^{\text{out}}) \log_2(1 + \gamma_{\text{th}}) \tag{5}$$

Step 2 The inverse rate matrix $\mathbf{R} \in \mathbb{R}^{M \times M}$ associated with all possible D2D links is computed as:

$$\mathbf{R}_{t,r} = \frac{1}{R_{tr}} \tag{6}$$

Also, $\mathbf{R}_{t,t} = 0 \quad \forall \quad t$.

Step 3 Since the end-to-end throughput of a series of links is the scaled harmonic mean[1] of the individual link rates, Dijkstra's algorithm [14] can be directly applied, with link weights given by the inverse rate matrix obtained above. This results in a throughput-optimal route from d_S to d_D which minimizes the sum of inverse rates, and consequently maximizes the end-to-end throughput.

The time complexity of Dijkstra's algorithm is also $\mathcal{O}(M^2)$, and hence the overall complexity of the proposed routing algorithm is $\mathcal{O}(M^2)$.

Thus, an optimal route in terms of achievable end-to-end throughput is obtained for a given value of target SINR threshold at the D2D receiver. The above recipe can be used to perform a one dimensional search over γ_{th} to obtain the globally optimal path and its associated SINR threshold. We now describe the link activation scheme used to transmit data over the optimal route, and provide analytical results for the achievable throughput, delay and system idle probability.

IV. Sequential Link Activation Based Data Transmission

In sequential link activation (SLA), each of the links in the throughput-optimal route is selected in a round-robin fashion, and is activated repeatedly in successive slots till its packet is delivered to the next node in the path. Only one D2D link is activated per slot, which ensures that the interference outage constraint imposed by the cellular network is always satisfied. A packet sent from transmitter d_t to receiver d_r in the optimal path is successful if $P_{tr}^{\min} \leq P_t^{\max}$, which, in turn, depends on the fading instantiation, as given in Step 3 of the algorithm in Sec. III-A. Hence, the time taken for a packet to reach the next node in the path is a geometric random variable with parameter given by the link outage probability p_{tr}^{out}. We now

[1]More precisely, the throughput is the harmonic mean multiplied by the number of links in the path.

analyze the end-to-end throughput, packet delay and system idle probability for SLA based data transmission over the optimal route, when the fading coefficients of the wireless channels between D2D nodes are independent and identically distributed Rayleigh random variables.

1) Delay and Throughput: The end-to-end delay in packet transmission is the sum of the expected number of time slots taken to transmit a packet successfully from a D2D transmitter, d_t, to the D2D receiver, d_r, for each link in the optimal path. For the link $d_t \rightarrow d_r$, the expected delay, w_{tr}^{SLA}, is given by

$$\begin{aligned} w_{tr}^{\text{SLA}} &= (1-p_{tr}^{\text{out}}) + 2p_{tr}^{\text{out}}(1-p_{tr}^{\text{out}}) + 3(p_{tr}^{\text{out}})^2(1-p_{tr}^{\text{out}}) + \cdots \\ &= \frac{1}{(1-p_{tr}^{\text{out}})}. \end{aligned} \tag{7}$$

The delay due to all the links in the route is then given by

$$w^{\text{SLA}} = \sum_{\substack{(t,r)\,\in\,\{(S,1),\\(1,2),\cdots,(K,D)\}}} w_{tr}^{\text{SLA}} \tag{8}$$

where K denotes the number of relays in the optimal route determined in the previous section. From Little's law, since there is at most one packet waiting to be transmitted over each link, the throughput of the link $d_t \rightarrow d_r$ is

$$T_{tr} = \frac{1}{w_{tr}^{\text{SLA}}}\log(1+\gamma_{\text{th}}). \tag{9}$$

The end-to-end throughput between the D2D source and destination pair is the scaled harmonic mean of the throughputs of individual links in the route, leading to the expression

$$T^{\text{SLA}} = \frac{1}{w^{\text{SLA}}}\log(1+\gamma_{\text{th}}). \tag{10}$$

2) System idle probability: The system is said to be in the idle state whenever the selected link is found to be infeasible and so the packet cannot be successfully transmitted through that link. The idle probability is of interest, as it measures the spectral reuse by the D2D nodes. Also, a network with a high system idle probability is likely to yield low end-to-end data throughput between the source and destination. For example, at higher values of target SINR threshold, the D2D links become infeasible more frequently due to the limited transmit power allowed by the interference outage constraint, which leads to the system being in idle state more frequently. System idle probability can thus be used to compare the efficiency of routes in terms of achievable throughput as well.

First, the probability of the link $d_t \rightarrow d_r$ being selected for data transmission is proportional to the delay introduced by it, and is given by

$$p_{tr}^{\text{sel}} = \frac{w_{tr}^{\text{SLA}}}{w^{\text{SLA}}}. \tag{11}$$

Thus, the system idle probability when the SLA scheme is used for data transmission is

$$\begin{aligned} p_{\text{out}}^{\text{SLA}} &= \sum_{\substack{(t,r)\,\in\,\{(S,1),\\(1,2),\cdots,(K,D)\}}} p_{tr}^{\text{out}} p_{tr}^{\text{sel}} \\ &= \frac{1}{w^{\text{SLA}}} \sum_{\substack{(t,r)\,\in\,\{(S,1),\\(1,2),\cdots,(K,D)\}}} \frac{p_{tr}^{\text{out}}}{1-p_{tr}^{\text{out}}}. \end{aligned} \tag{12}$$

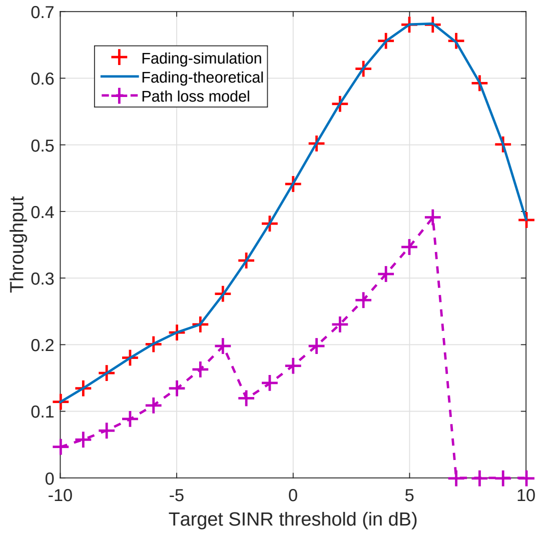

Fig. 2. Comparison of the throughput performance of the proposed algorithm and algorithm in [11].

This completes the throughput analysis of the routing algorithm. Next, we present simulation results to illustrate its performance.

V. Simulation Results

The simulation setup consists of $N = 2$ BSs and $M = 10$ D2D users with channel fading coefficients drawn from $\mathcal{CN}(0,1)$. The geographical distribution of the D2D users and BSs are the same as in [11]. The interference threshold at the BSs, $\gamma_{\text{bs}} = 3$ dB and $p_b = 0.4$. The path loss exponent $\eta = 4$ and the reference distance is taken to be 1 m. We determine the end-to-end D2D throughput as a function of the target SINR threshold, γ_{th}.

We compare the performance of our routing algorithm against the algorithm proposed in [11], which ignores the fading in the wireless channel (and only considers the path loss in the signal). However, to make the comparison fair, we consider a modified version of the algorithm in [11], by accounting for the fading in the channel between the D2D nodes and the BSs in the route design phase. We use the interference outage constraint, p_b, to calculate the maximum allowed transmit power as given in (1) of Sec. III-A. This equation replaces the one in Step 4 of the algorithm in [11], and ensures that the maximum allowed transmit powers of the D2D nodes are the same in both the algorithms. Hence, the achieved data rates are comparable to each other.

The results in Figure 2 show that our algorithm achieves significant throughput gains, *i.e.,* approximately 50%, compared to the algorithm in [11] because the link outages due to fading in the D2D links have been considered in the route design. In addition, our algorithm is able to find a feasible route at higher SINR threshold values too. This is because the effective rates of the D2D links are nonzero even at higher target rates, unlike [11], where the source and destination

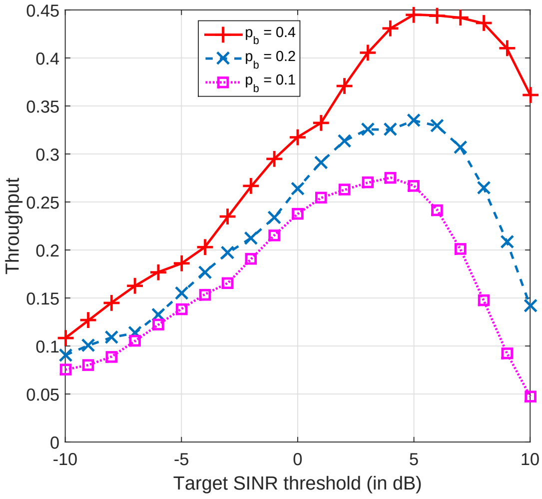

Fig. 3. D2D throughput for different values of interference outage probability.

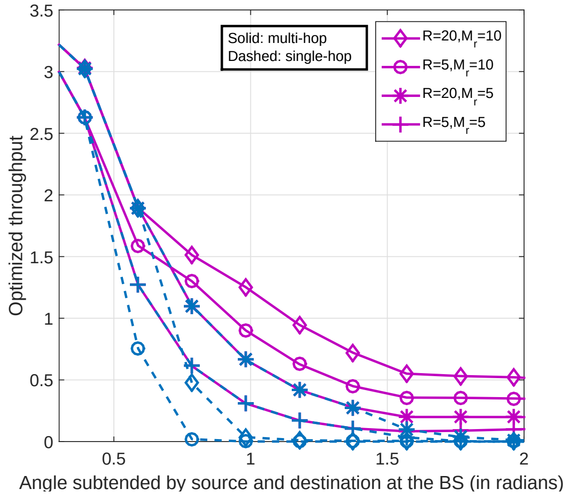

Fig. 4. Optimized D2D throughput achieved with angle subtended by the source and destination at the BS.

become disconnected at high γ_{th}. We also note the perfect match between the simulated throughput and the theoretical expression derived in (10).

The results in Figure 3 illustrate the data rates obtained under different probabilistic guarantees imposed on the interference constraint. As the cellular network allows for more interference outages, D2D transmitters exploit the availability of higher maximum allowed powers. This allows the links to meet the target SINR constraint more frequently, resulting in increased data throughput.

To understand the throughput variation with distance between the D2D source and destination, we use a single-cell simulation setup where the node locations are varied according to the angle subtended by them at the BS. Here, the source and destination are allowed to skirt around the BS with an angular separation between them while M_r potential D2D relay nodes are placed uniformly on the circle formed by the skirt radius, R, for $R = 5$ and 20 units. The plots in Figure 4 confirm that the end-to-end throughput is maximum when the nodes are closest to each other and the direct link is available for communication. Also, the gain in throughput due to multi-hop D2D (compared to single-hop D2D) becomes more and more significant as the angle subtended at the BS increases.

Figure 5 shows the throughput as a function of the SINR threshold for two different skirt radii. The throughput is higher at higher R. This is because the maximum allowed power under the interference outage constraint is higher, allowing the D2D nodes to achieve higher rates. Also, the target SINR threshold which achieves maximum throughput decreases with increase in angular separation and decrease in skirt radius.

In Fig. 6, we illustrate the improvement in D2D throughput when different numbers of D2D relay nodes (denoted by M_r) are available in the network. The throughput is improved due to the availability of more D2D links to choose from to obtain the throughput-optimal route. The plots reiterate that a multi-hop route can offer significantly better throughput than

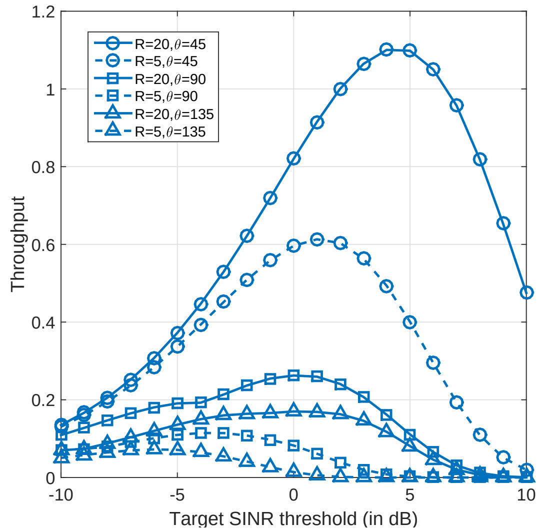

Fig. 5. D2D throughput achieved with different angles subtended by the source and destination at the BS for two different skirt radii.

single-hop D2D (the curve with $M_r = 0$). To generate these results, the locations of the BS, source and destination are kept fixed, and the locations of other D2D nodes are chosen uniformly at random within an area of interest. The throughput values are obtained by averaging the results across 100 random deployments of D2D relay nodes.

Finally, Figure 7 illustrates the behavior of the system idle probability which increases with increasing target SINR. At $\gamma_{\text{th}} = -4$ dB, the idle probability drops when the optimal route changes from direct link communication to a 2-hop path and increases thereafter, as more links become infeasible under the interference outage constraint imposed by the cellular network. Further, the plot verifies the correctness of the theoretical expression derived in Sec. IV-2.

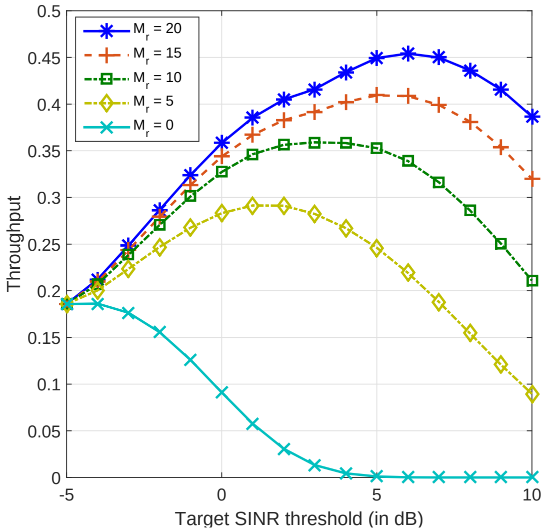

Fig. 6. D2D throughput for varying number of potential relay nodes.

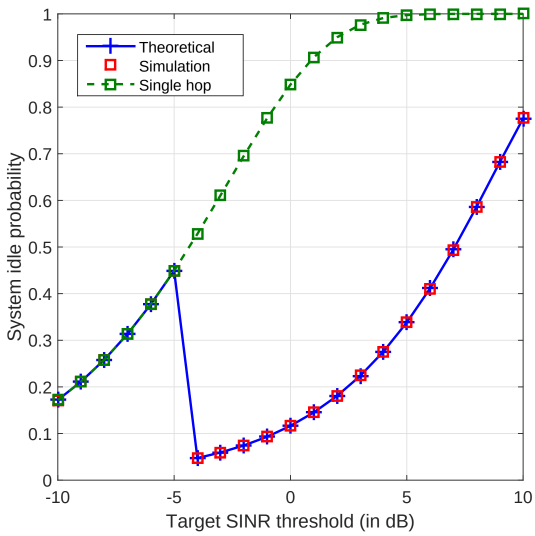

Fig. 7. System idle probability when $\gamma_{\text{bs}} = 3$ dB and $p_b = 0.4$.

VI. Conclusion

In this work, we proposed routing algorithms for maximizing the end-to-end throughput between a given D2D source and destination pair, under interference constraints imposed by the cellular network, with a fixed-rate communication model between D2D nodes in the network. We computed the effective rates achieved by the links comprising the optimal path by considering the probabilistic interference constraint at the BSs and a target SINR threshold at the D2D receiver. We proposed optimal routing and power allocation algorithms which are computationally efficient and easy to implement in practice. We considered a sequential link activation scheme for data transmission, which adheres to the interference outage constraint, and obtained analytical expressions for data throughput, delay and system idle probability.

Our results showed that multi-hop routing can offer significantly better throughput compared to single-hop D2D communications. Further, considering the effect of channel fading in the routing phase leads to better throughput compared to designs based on the path loss only. We also illustrated the effect of separation between source and destination D2D nodes, the distance from the BS, and availability of potential D2D relay nodes, on the end-to-end data rates, via simulations. Future work could consider data buffer-aided opportunistic link activation instead of SLA, where any link that is feasible in a given slot can be activated, thereby reducing the system idle probability and improving throughput, at the cost of a higher average packet delay.

References

[1] J. Gu, S. J. Bae, S. F. Hasan, and M. Y. Chung, "Heuristic algorithm for proportional fair scheduling in d2d-cellular systems," *IEEE Transactions on Wireless Communications*, vol. 15, no. 1, pp. 769–780, Jan 2016.

[2] H. Tang and Z. Ding, "Mixed mode transmission and resource allocation for d2d communication," *IEEE Transactions on Wireless Communications*, vol. 15, no. 1, pp. 162–175, Jan 2016.

[3] F. Wang, Y. Li, Z. Wang, and Z. Yang, "Social-community-aware resource allocation for d2d communications underlaying cellular networks," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 5, pp. 3628–3640, May 2016.

[4] K. Venugopal, M. C. Valenti, and R. W. Heath, "Device-to-device millimeter wave communications: Interference, coverage, rate, and finite topologies," *IEEE Transactions on Wireless Communications*, vol. 15, no. 9, pp. 6175–6188, Sept 2016.

[5] S. Kim and A. Zaji, "Statistical modeling and simulation of short-range device-to-device communication channels at sub-thz frequencies," *IEEE Transactions on Wireless Communications*, vol. 15, no. 9, pp. 6423–6433, Sept 2016.

[6] T. Peng, Q. Lu, H. Wang, S. Xu, and W. Wang, "Interference avoidance mechanisms in the hybrid cellular and device-to-device systems," in *2009 IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*, Sept 2009, pp. 617–621.

[7] X. Chen, L. Chen, M. Zeng, X. Zhang, and D. Yang, "Downlink resource allocation for device-to-device communication underlaying cellular networks," in *2012 IEEE 23rd International Symposium on Personal, Indoor and Mobile Radio Communications - (PIMRC)*, Sept 2012, pp. 232–237.

[8] J. M. B. da Silva, G. Fodor, and T. F. Maciel, "Performance analysis of network-assisted two-hop d2d communications," in *2014 IEEE Globecom Workshops (GC Wkshps)*, Dec 2014, pp. 1050–1056.

[9] S. Wen, X. Zhu, Y. Lin, Z. Lin, X. Zhang, and D. Yang, "Achievable transmission capacity of relay-assisted device-to-device (d2d) communication underlay cellular networks," in *Vehicular Technology Conference (VTC Fall), 2013 IEEE 78th*, Sept 2013, pp. 1–5.

[10] P. Ren, Q. Du, and L. Sun, "Interference-aware routing for hop-count minimization in wireless d2d networks," in *Communications in China - Workshops (CIC/ICCC), 2013 IEEE/CIC International Conference on*, Aug 2013, pp. 65–70.

[11] V. Bhardwaj and C. R. Murthy, "On optimal routing and power allocation for D2D communications," in *Proc. ICASSP*, 2015.

[12] B. G. Choi, J. S. Kim, M. Y. Chung, J. Shin, and A. S. Park, "Development of a system-level simulator for evaluating performance of device-to-device communication underlaying lte-advanced networks," in *2012 Fourth International Conference on Computational Intelligence, Modelling and Simulation*, Sept 2012, pp. 330–335.

[13] M. S. Ali and N. B. Mehta, "Modeling time-varying aggregate interference in cognitive radio systems, and application to primary exclusive zone design," *IEEE Transactions on Wireless Communications*, vol. 13, no. 1, pp. 429–439, January 2014.

[14] D. P. Bertsekas, *Dynamic Programming and Optimal Control*, 2nd ed. Athena Scientific, 2000.